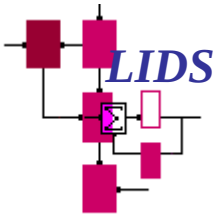

Atmospheric Optical Communications

Architecture, System Design and Concept Demonstration of a Battlefield Agile-beam Optical Communication System

Vincent W. S. Chan
Jeffrey H. Shapiro
Franco N. C. Wong

Laboratory for Information and Decision Systems
Research Laboratory of Electronics
Department of Electrical Engineering and Computer Science
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

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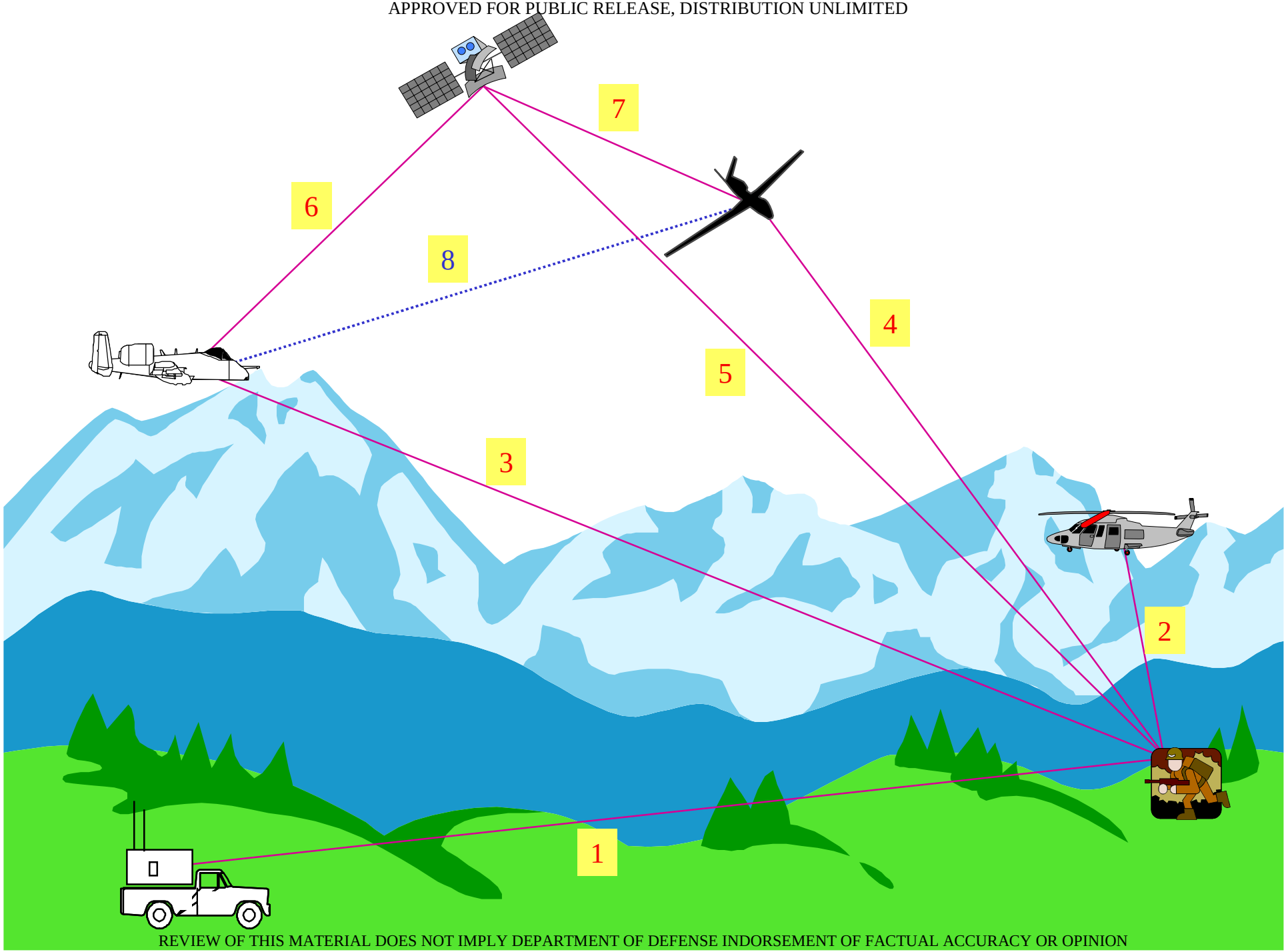

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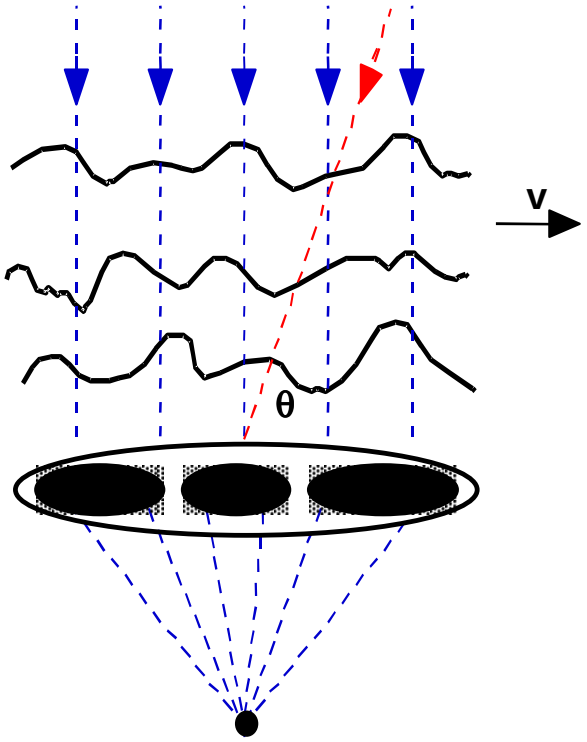
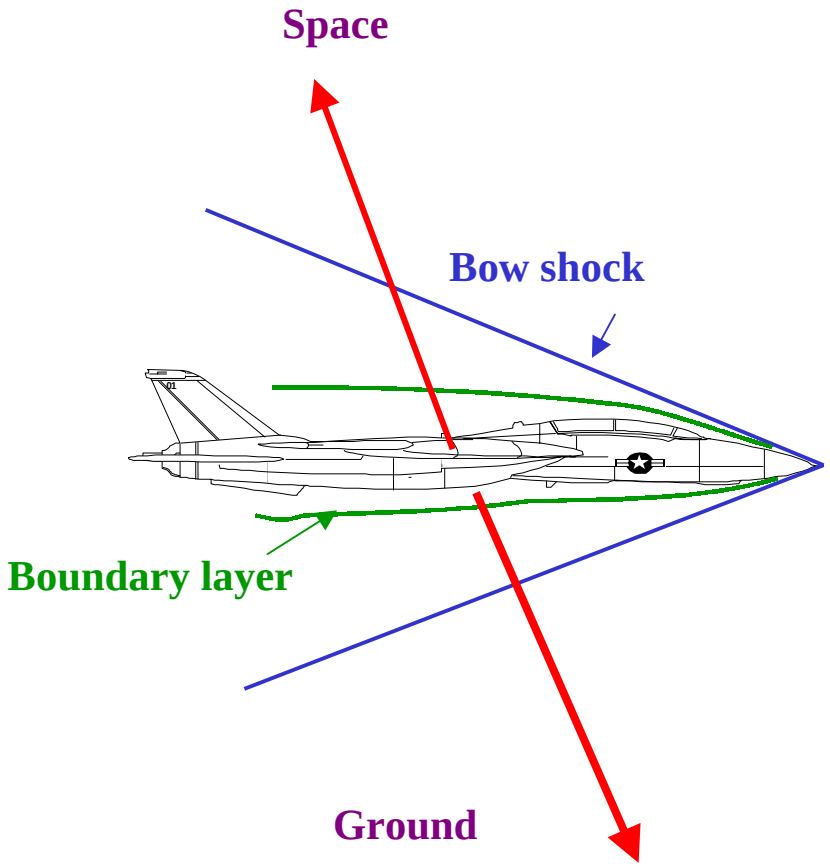
Atmospheric Optical Communications

LIDS

Far-away turbulence : scintillation
Near-by turbulence : phase distortion



r_o = effective collector diameter
$\tau_o = r_0/v$ = time constant
θ_o = isoplanatic angle



Boundary layer turbulence & bow shock creates rapid beam steering and poor strehl

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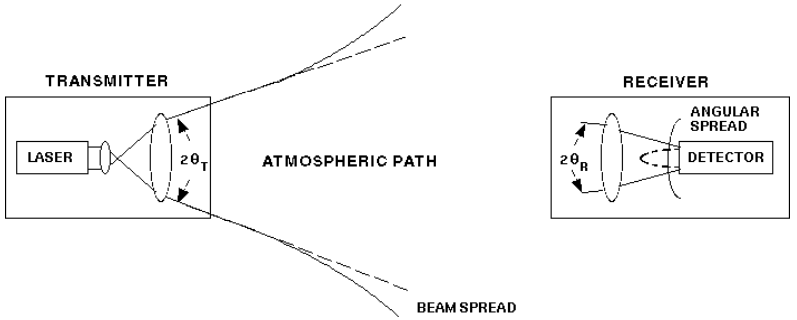
Atmospheric Optical Wave Propagation

Free-Space vs. Atmospheric Propagation

- Molecular Constituents
- Atmospheric Turbulence
- Clouds, Fog, Snow, and Rain
- Smoke and Dust

Line-of-Sight Propagation Phenomena

- Attenuation, Depolarization
- Beam Spread, Angular Spread



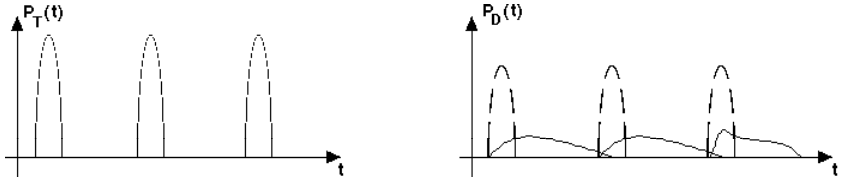
Atmospheric Turbulence

- Refractive-Index Fluctuations
- Kolmogorov Inertial-Subrange Spatial Spectrum
- Taylor's Hypothesis (Frozen-Flow) Temporal Behavior

Extended Huygens-Fresnel Principle

- Mutual Coherence Function Behavior
- Scintillation Behavior

- Multipath Spread: intersymbol interference
- Doppler Spread: time-dependent fading



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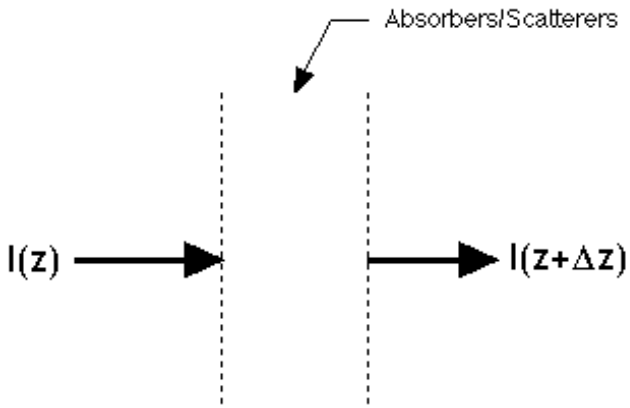
Atmospheric Optical Wave Propagation

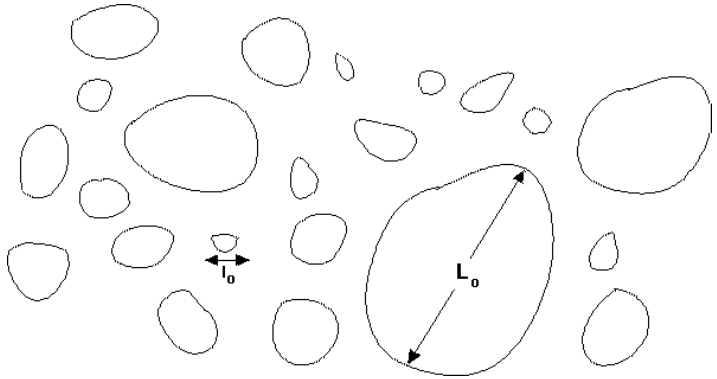
The Beer-Lambert Law

- Absorption, Scattering and Extinction

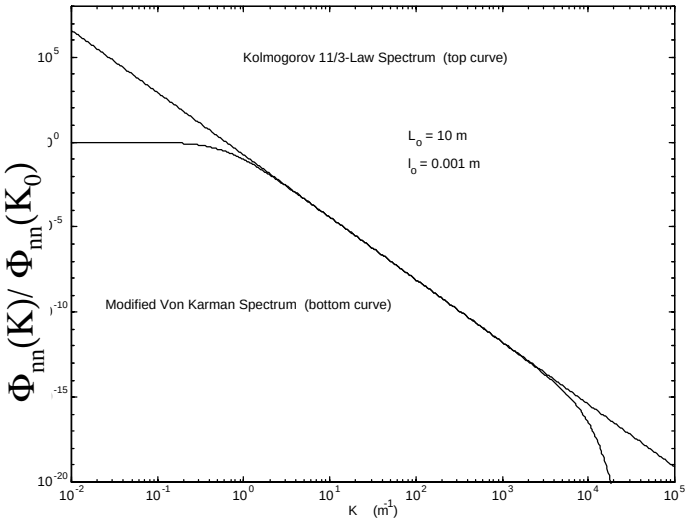


Atmospheric Turbulence

- $\Delta T \sim 1K$ leads to $\Delta n \sim 10^{-6}$



Modified Von Karman Spatial Spectrum



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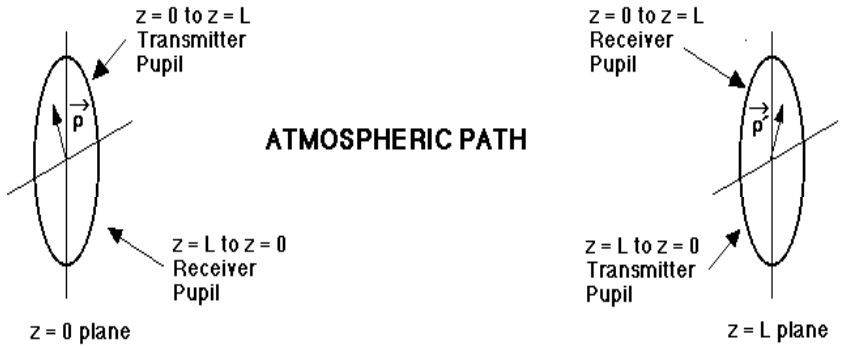
Extended Huygens-Fresnel Principle

LIDS

Quasimonochromatic, Scalar-Wave Propagation

Atmospheric Green's Function

Instantaneous Atmospheric Reciprocity



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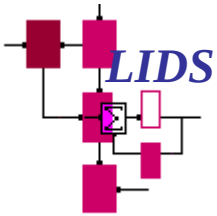
Extended Huygens-Fresnel Principle



Green's Function Statistics

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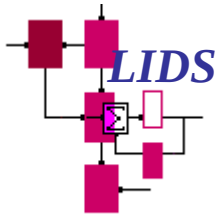
Extended Huygens-Fresnel Principle



Beam Spread and Angular Spread

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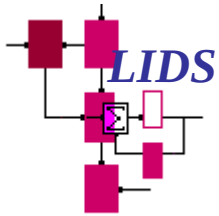
Extended Huygens-Fresnel Principle



Scintillation: Log-Amplitude Variance

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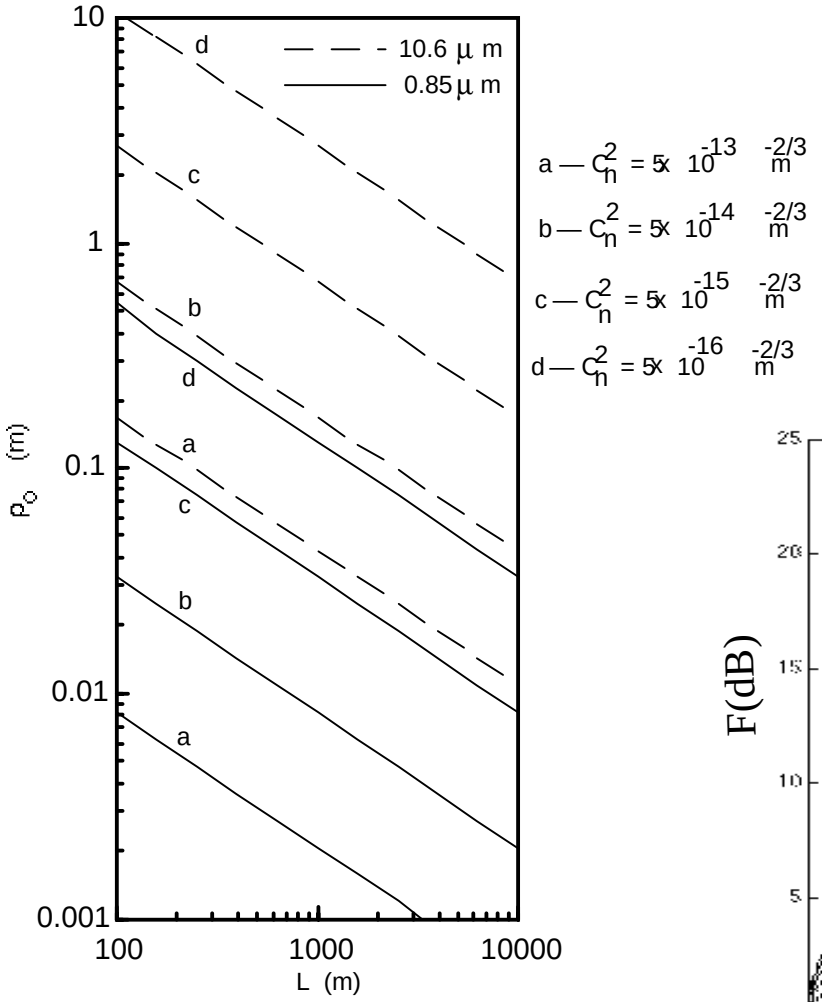
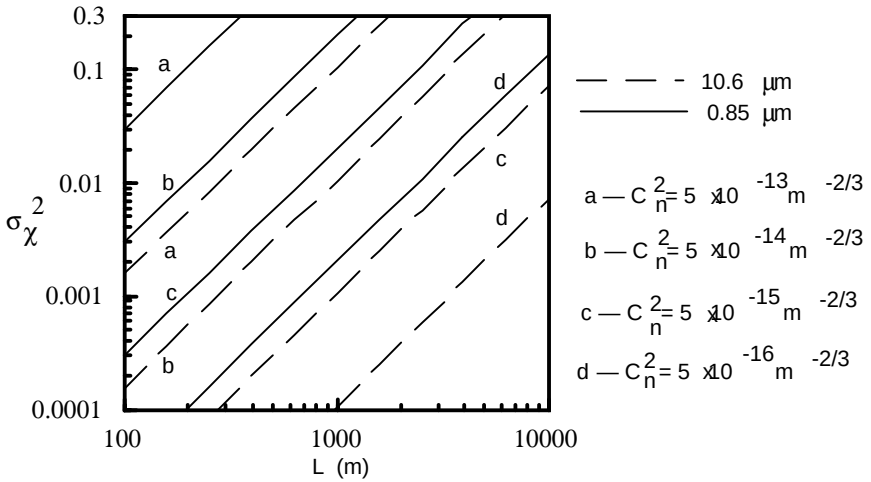
Extended Huygens-Fresnel Principle

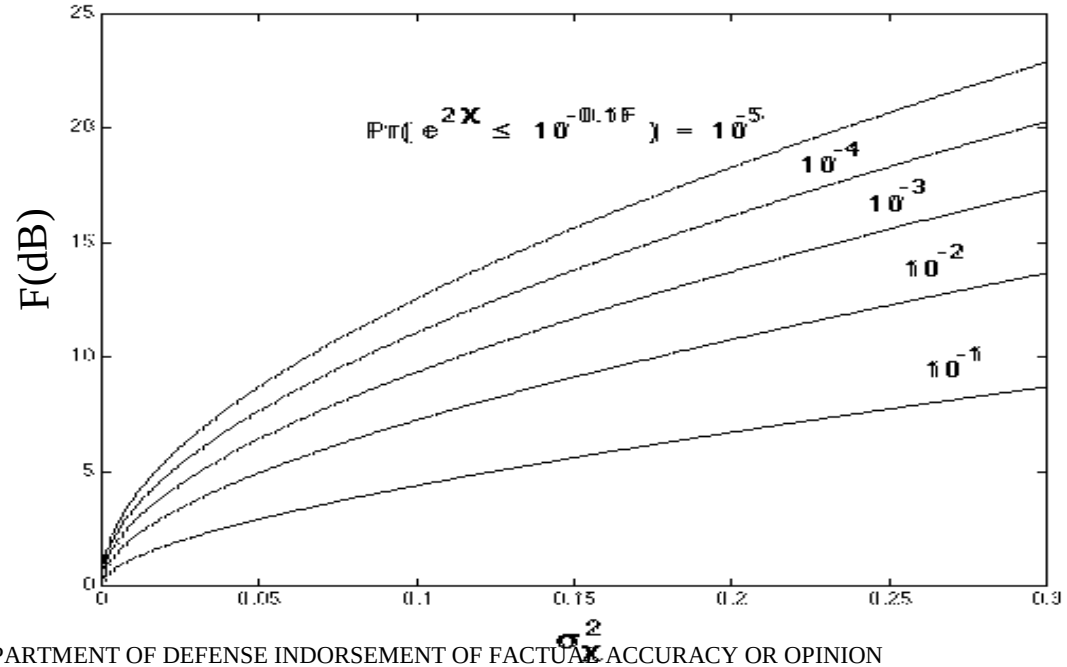
Horizontal Path Coherence Length



HORIZONTAL PATH LOG-AMPLITUDE VARIANCE



Fade Depths for Lognormal Statistics



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Extended Huygens-Fresnel Principle

LIDS

$$\Phi_n(\kappa) = 0.033\, C_n^2\, \kappa^{-11/3}$$

Kinetic Energy Associated with Large Eddies is Redistributed to Smaller Eddies Without Loss

$$r_o = 0.185\left\{\frac{\lambda^2}{\sec(\zeta)\int C_n^2(h)\,dh}\right\}^{3/5}$$

Turbulence Intensity Coherence Length

$$\tau_o = 0.058\left\{\frac{\lambda^2}{\sec(\zeta)\int C_n^2(h)\,v^{5/3}(h)\,dh}\right\}^{3/5}$$

Turbulence Time Constant

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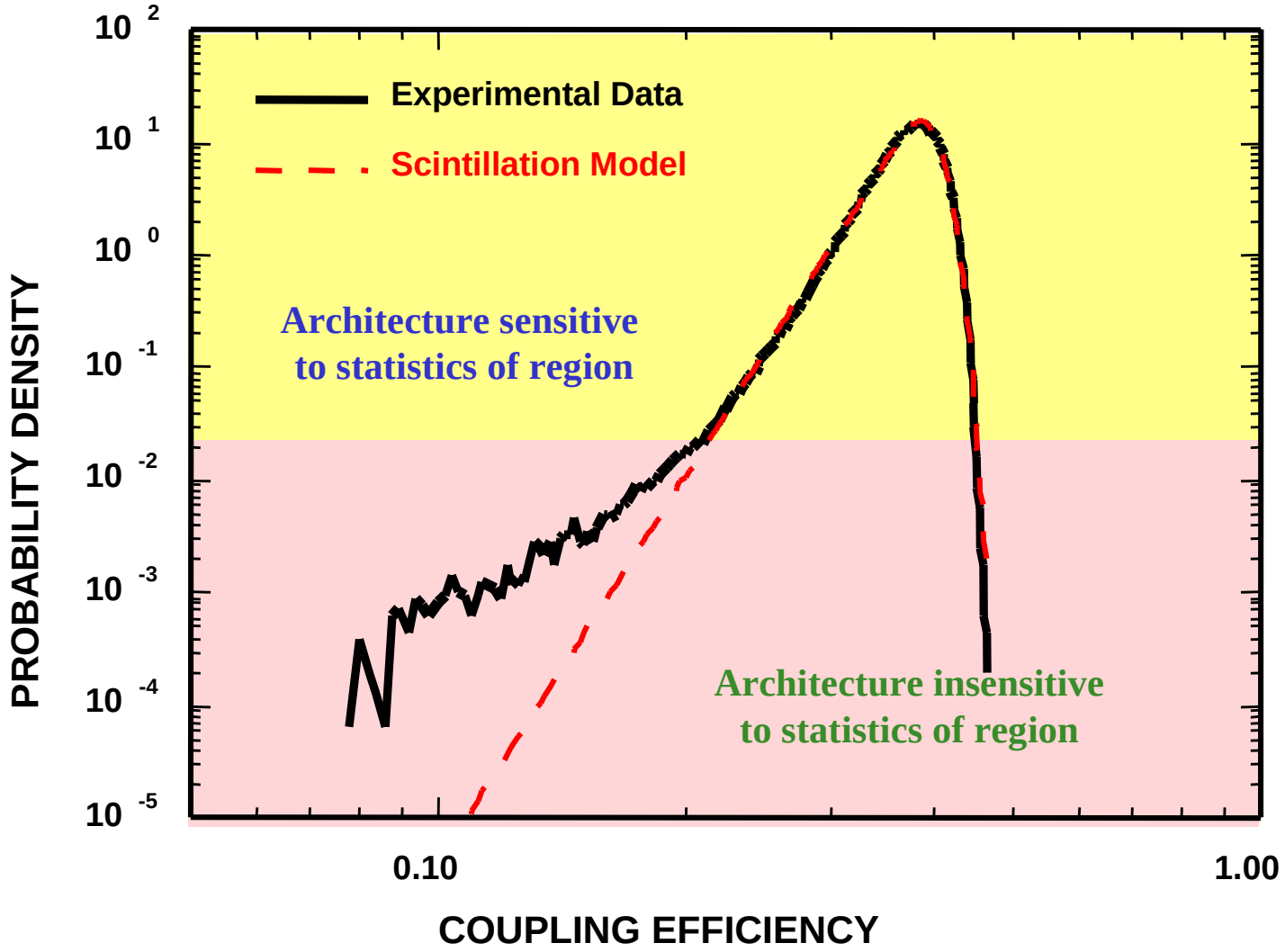
Scintillation Statistical Models



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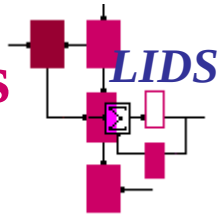
Turbulence Mitigation Transmitter Techniques



- **Tranmitter averaging**
  - ***multiple transmitters (?)***
  - ***dispersion***
- **Predistortion**
  - ***reciprocity a concern***

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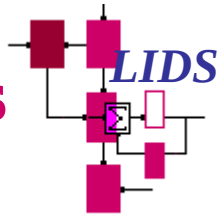
Turbulence Mitigation Receiver Techniques



- **Receiver aperture averaging**
  - ***photon bucket***
  - ***multiple incoherent receivers and power combining***

  Incoherent combining gains as $N^{1/2}$

- **Coherent compensation**
  - ***deformable mirror, MEM***
  - ***coherent receiving array***
  - ***non-linear four-wave mixing***

  Coherent combining gains as N but more complex

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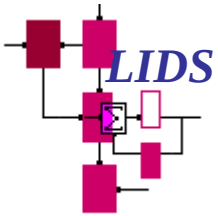
Turbulence Mitigation Techniques



- **Time diversity**
- **Coding and interleaving**
  - ***long interleaver size a burden for high rates***
  - ***space-time coding***
- **Frequency diversity**
  - ***complex and wideband***
- **Transport layer protocol**

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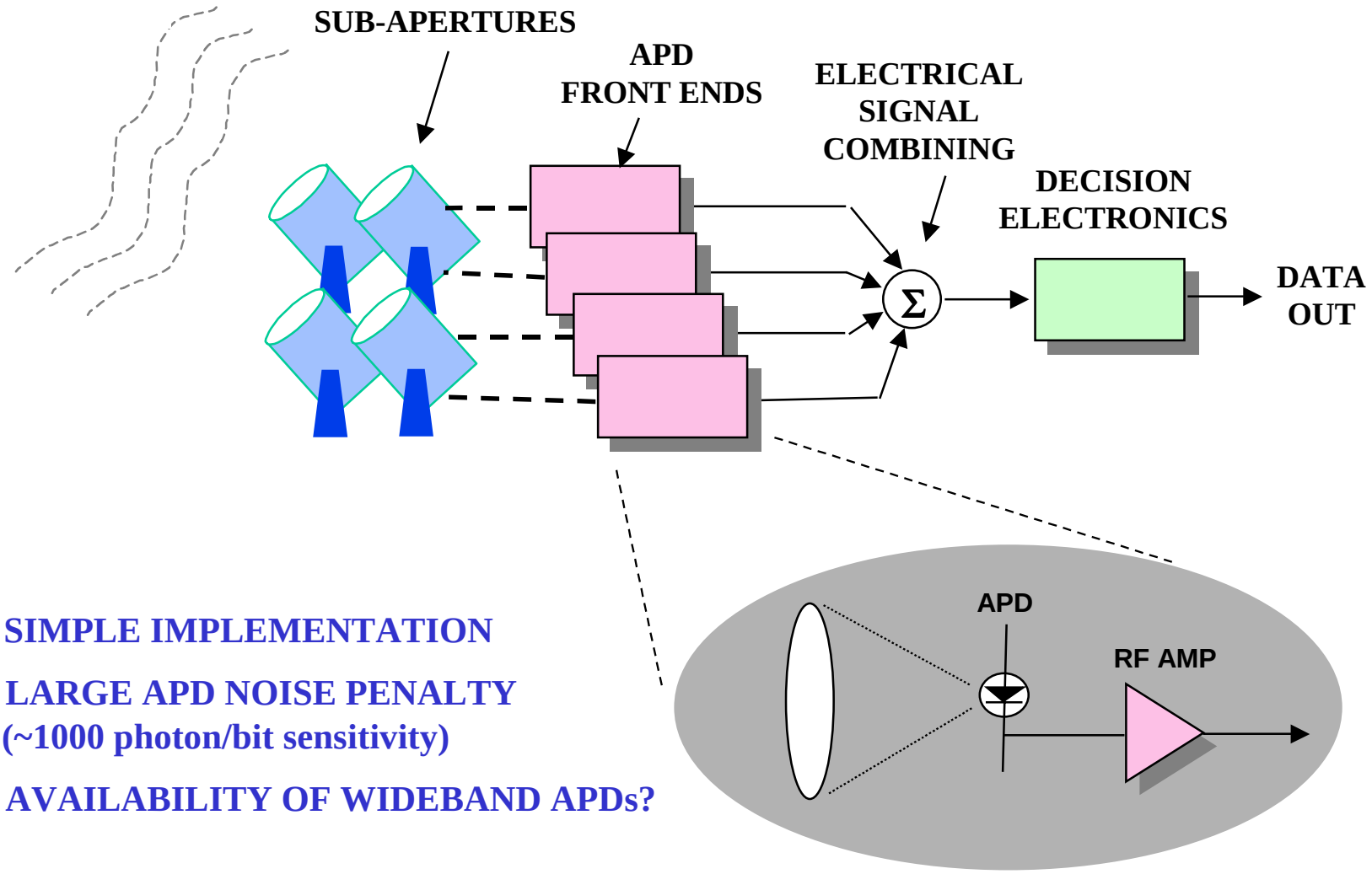
APD Multi-mode Receivers



- **SIMPLE IMPLEMENTATION**
- **LARGE APD NOISE PENALTY (~1000 photon/bit sensitivity)**
- **AVAILABILITY OF WIDEBAND APDs?**

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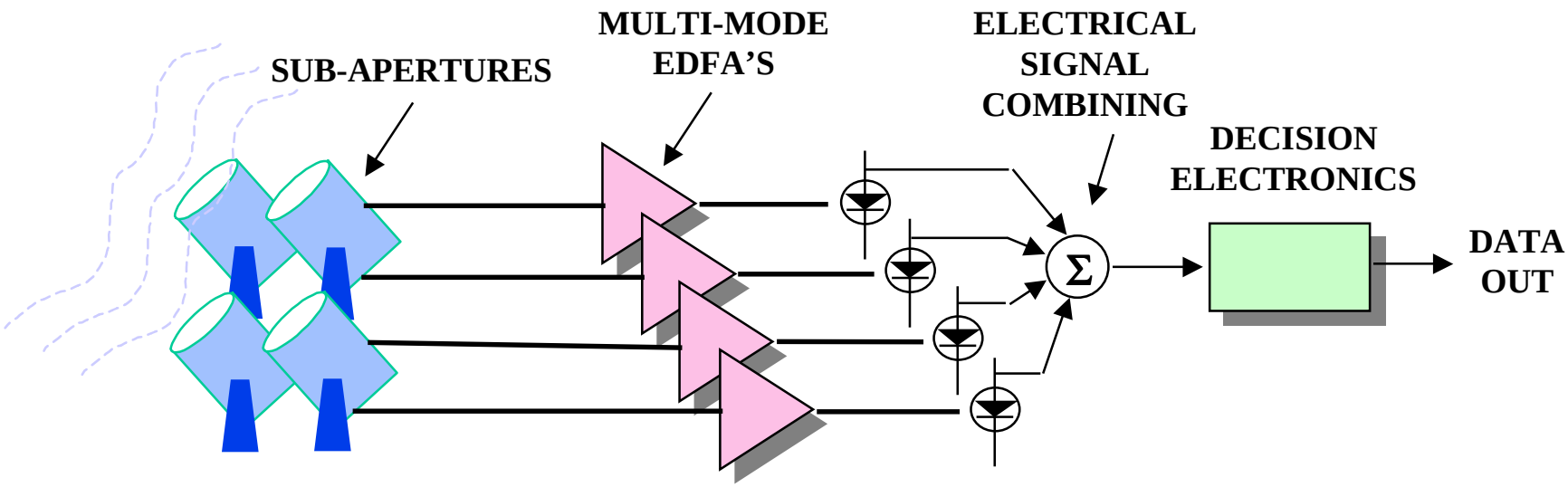
Multi-mode EDFA Receivers



- LESS COMPLEX THAN ADAPTIVE OPTICS
- NO SERVO CONTROL (no Greenwood frequency dependence)
- REQUIRES DEVELOPMENT WORK
- KEY ISSUES
  - FIBER COUPLING EFFICIENCY
  - NOISE PENALTY
  - DISPERSION

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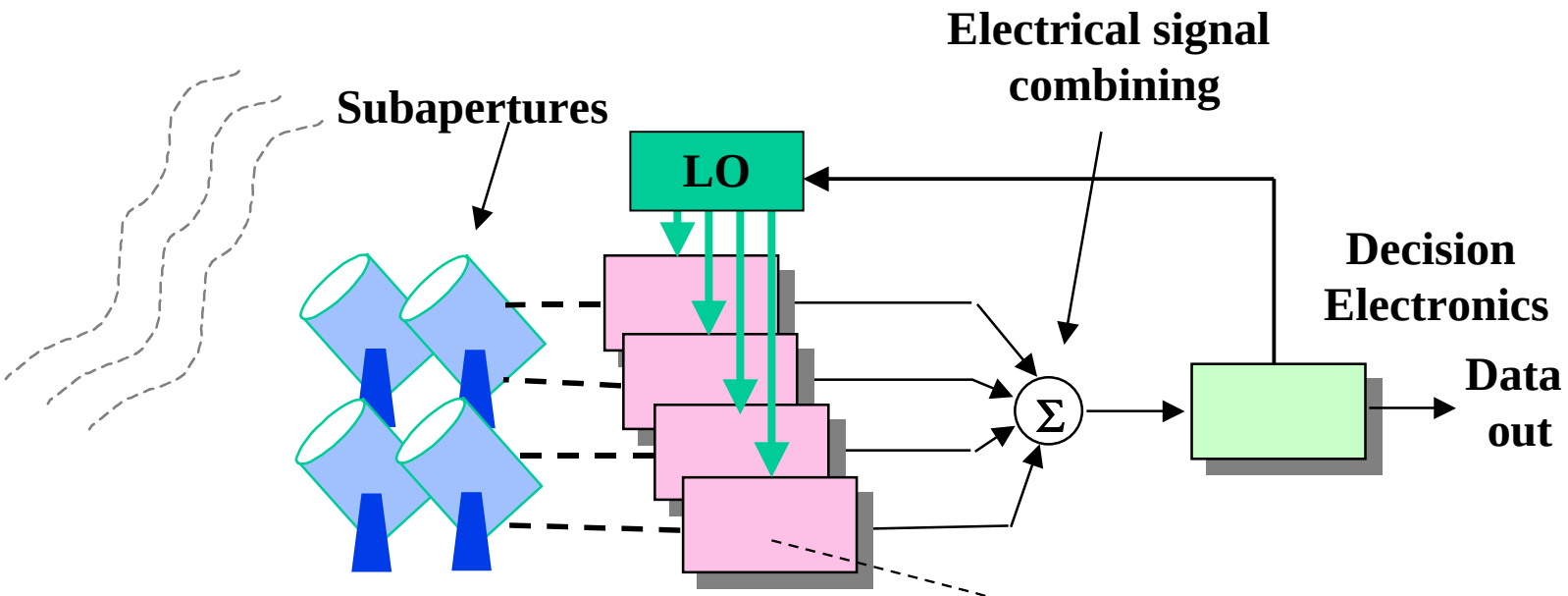
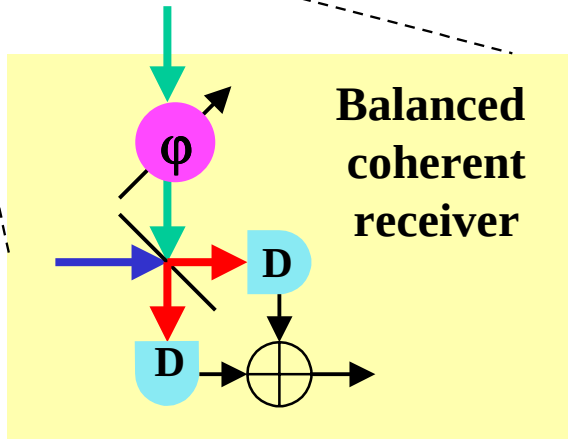
Multi-mode Coherent Receivers





- Coherent receiver array
- Sensitive balanced receiver
- Each element requires angle and phase tracking
- Feedback control

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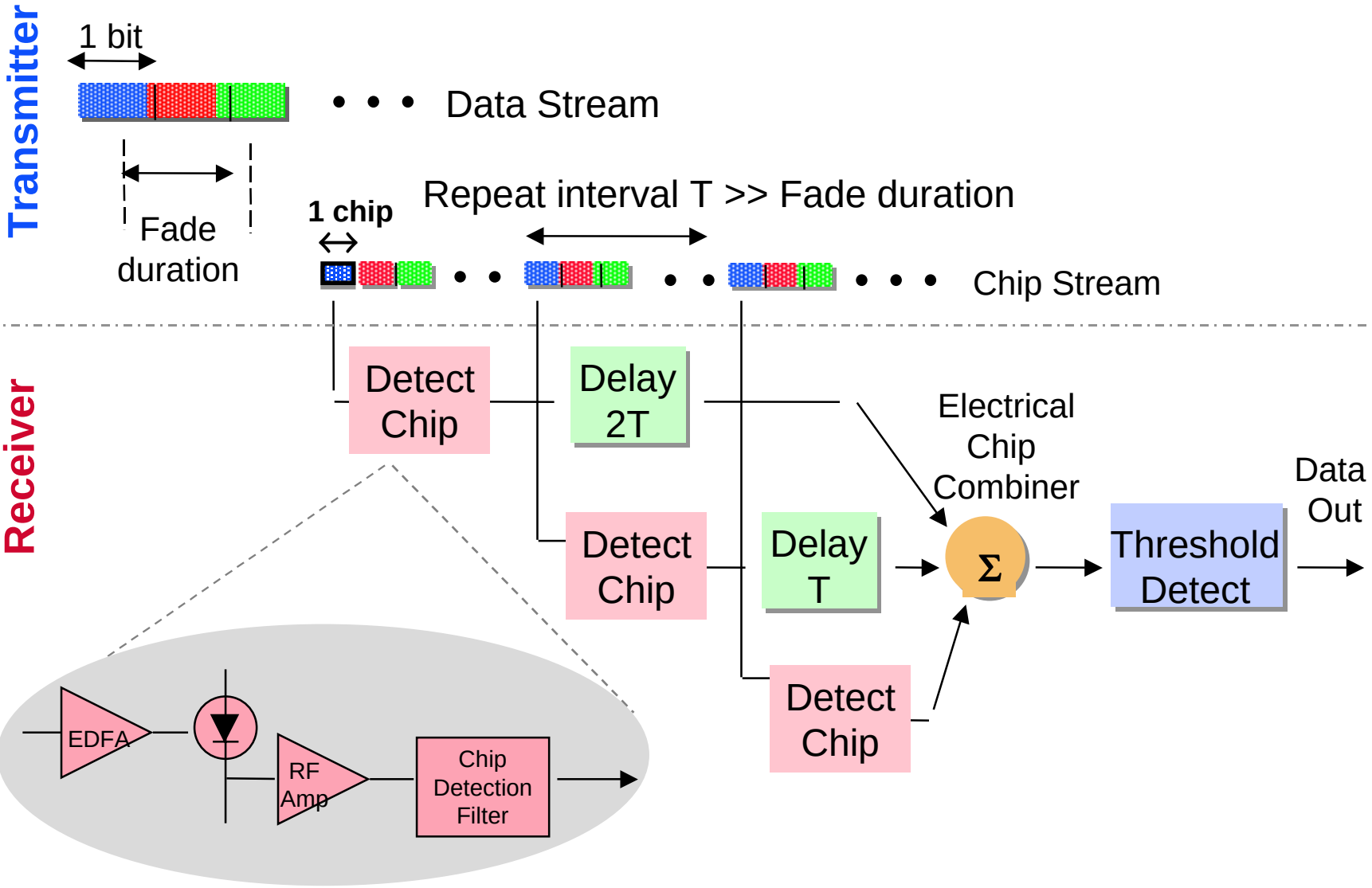
Time Diversity Transmission



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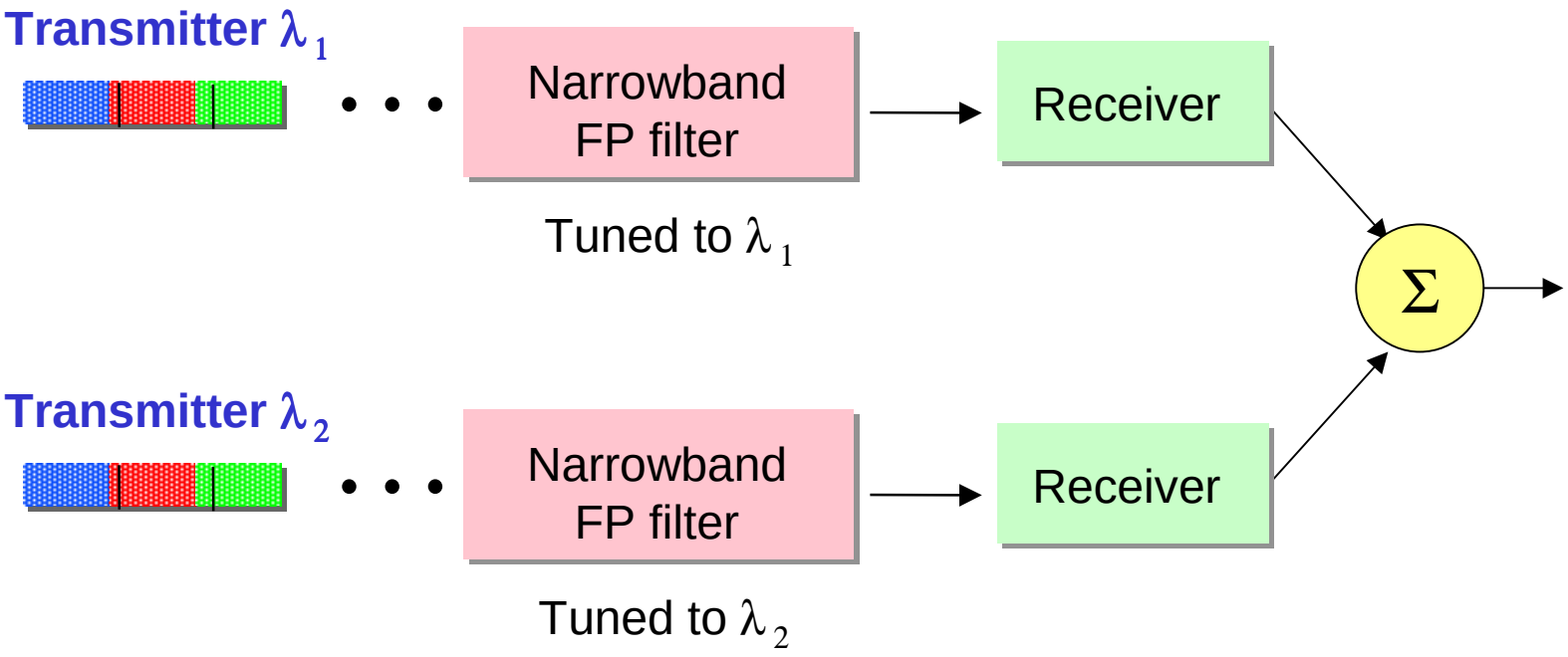
Frequency Diversity Transmission



$|\lambda_1 - \lambda_2| > ?$ nm

Optimum processing vs simple suboptimum combining

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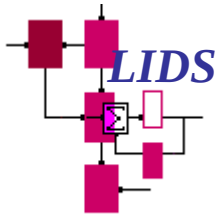
Outdoor-Path Test Bed Facilities



- **High data rate (~1 Gb/s) 1.55-μm communication system**
- **Commercial off-the-shelf components and subsystems**
- **Interface with existing fiberoptic networks**
- **Mitigation techniques for handling naturally occurring atmospheric turbulence:**
  - **Spatial diversity reception**
  - **Time diversity transmission**
  - **Frequency diversity transmission**

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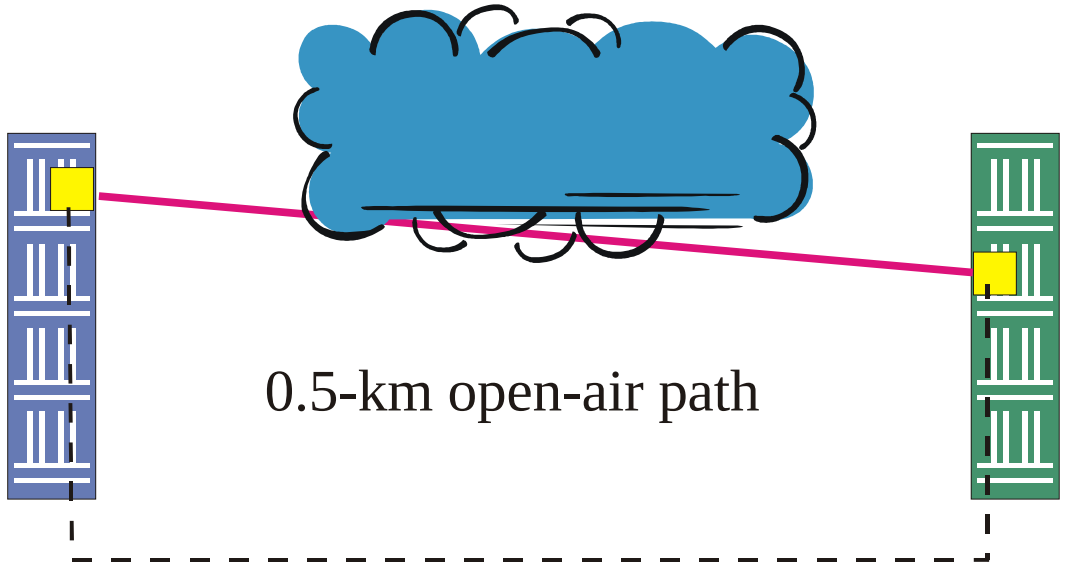
Experimental Concept Demonstration



- **Outdoor link to handle prevailing atmospheric conditions**
- **Communication performance using transmitter and receiver diversity combining techniques and modulation protocols**
- **Verification of statistical models and system designs**
- **Feedback for system design/optimization research**

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